2005

Dual header pulse interval modulation for digital communication systems

Maung Tun Tun Lynn
San Jose State University

DUAL HEADER PULSE INTERVAL MODULATION FOR DIGITAL COMMUNICATION SYSTEMS

A Thesis

Presented to

The Faculty of the Department of Electrical Engineering

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Maung Tun Tun Lynn

August 2005

UMI Number: 1429438

INFORMATION TO USERS

APPROVED FOR THE DEPARTMENT OF

ELECTRICAL ENGINEERING

Dr. Robert Morelos-Zaragoza

(Advisor)

Dr. Avtar Singh

(Co-Advisor)

Thuy T. Le

Dr. Thuy Le

(Co-Advisor)

APPROVED FOR THE UNIVERSITY

Thea I. Williamson 8/11/05

ABSTRACT

DUAL HEADER PULSE INTERVAL MODULATION FOR

DIGITAL COMMUNICATION SYSTEMS

by

Maung Tun Tun Lynn

This thesis presents a digital communications system with the Dual Header Pulse Interval Modulation (DHPIM). In particular, a single user transceiver based on DHPIM is proposed. The system uses Pseudo Random Noise chips at a wide bandwidth spectrum. DHPIM is a pulse modulation that separates pulses by a number of time slots depending on the data to be transmitted. This scheme is more efficient than the Pulse Position Modulation in terms of transmission rate and bandwidth requirements. The average data rate of proposed system is 250 Mbps. The study was based on MATLAB simulations and knowledge of DHPIM and Direct Sequence Spread Spectrum (DSSS) systems. A DHPIM system for digital transmission is presented and its performance is evaluated.

ACKNOWLEDGEMENTS

I would like to thank all individuals who supported me and were involved in one way or another in the preparation of this thesis. With the biggest contribution to this thesis, I would like to thank my thesis supervisor Professor Robert M Zaragoza. His extraordinary culture and knowledge made possible and inspired me to do this thesis. Professor Zaragoza managed to re-direct my thinking towards new dimensions to meet professional system approach.

I would also like to thank my co advisors, Dr. Avtar Singh and Dr. Thuy Le, for their time and precious comments furnished on my thesis. My sincere thanks also go to Dr. Nawras Aldibbiat from Sheffield Hallam University, United Kingdom, the inventor of DHPIM concept and Tim Becker who provided Multi-path simulation block.

Last not least, my sincere thanks to my parents and friends. Because of their financial and spiritual support, I have been able to study at an advanced academic level in Telecommunications.

TABLE OF CONTENTS

LIST OF SYMBOLS

BW_{3dB}	3dB Bandwidth
$gm(t)$	Gaussian Monocycle
$GM(f)$	Fourier Transformation of Gaussian Monocycle
f_c	Center Frequency
T_s	Single Time Slot Duration
T_f	Symbol Repetition Time

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS DEFINITION

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CDMA	Code Division Multiple Access
DHPIM	Dual Header Pulse Interval Modulation
DSSS	Direct Sequence Spread Spectrum
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
IEEE	Institute of Electrical and Electronics Engineers
OOK	ON OFF Keying
PG	Processing Gain
PN	Pseudo-random Noise
PPM	Pulse Position Modulation
PSD	Power Spectral Density
Rx	Receiver
TH	Time Hopping
Tx	Transmitter
UWB	Ultra Wide Band

1 Purpose and Scope

In newer wireless communications systems, the data rate is increasing and the applications of wireless communication are becoming important. However, the gap between the requirements of transmission speed and the data rate that can be offered still exists. This thesis discusses a new wireless transmission standard that offers a higher data rate: it presents a system with pulses that not only have the short time duration for faster transmission rate but also meet the power spectral constraint of Federal Communications Commission. The thesis evaluates the performance of a simulated model and the results. The simulated model is called the Dual Header Pulse Interval Modulation (DHPIM) on Ultra Wide Band (UWB). Potentially, UWB has the high data rate. The UWB system is very different compared to conventional wireless communication systems. Therefore, there are many challenges, such as modulation techniques, transmitted power, and the data rate limits of the UWB receiver, when designing a UWB system that does not exist in conventional wireless systems. Analytic results for the transmission rate, slot duration, bandwidth, power spectral density, and noise effect of a complete system are presented and where appropriate compared with other systems.

This document does not cover an exhaustive examination of the DHPIM system on UWB. Only once this system is integrated into a real system, the actual performance of the device can be completely understood. It is also understood that this project may go through further research process, and that several known improvements should be performed by this process. The topics listed above do not cover the entire picture of the

UWB system. Issues such as channel estimations and modeling, security problems, error correction, and UWB antenna design are also very critical, but are outside of the scope of this thesis.

The goal of the system simulation is to derive specifications for receiver and transmitter blocks and study the system performance. The experiment was based on existing knowledge of the DHPIM system, related modulation technology, and the preliminary properties of the narrow transmission pulses.

Table 1-1 Proposed Specifications for the System.

Parameters	Description
DHPIM with DSSS	
Modulation	Dual Header Pulse Interval Modulation (8 bits/symbol)
Chip Duration	0.6 nsec
Spreading Code Length	12
Frame Length	7.2 nsec
Error Correction	None
Pulse Waveform	Gaussian monocycle
Throughput	7.8 Mbps – 500 Mbps (250 Mbps Average)

The thesis covers a detailed examination of DHPIM system in Chapter 2. The definition of UWB, the features, related legal issues, signal representation, transmitted power, and the modulation schemes are addressed in Chapter 3. Chapter 4 introduces the Spread Spectrum systems. Chapter 5 describes the simulated system and presents corresponding results. Chapter 6 presents conclusions and recommendations for further research.

2 Dual Header Pulse Interval Modulation

A new digital pulse time modulation technique known as Dual Header Pulse Interval Modulation (DHPIM) which was introduced by Dr. Nawras Aldibbiat from Sheffield Hallam University, United Kingdom, has been proposed in this thesis. DHPIM has a higher transmission rate compared to that of Pulse Position Modulation (PPM) and Pulse Interval Modulation (PIM), with shorter frame length. It requires a simple frame synchronization at the receiver (Aldibbiat, Ghassemlooy, and Saatchi, 192). The DHPIM not only solves the problem of frame synchronization by initiating each frame with one of two different types of header pulses at the start of each frame, but also improves the transmission bandwidth by eliminating the unused time slots as in PPM. Simulated results show the potential of this new scheme for application where transmission rate enhancement is at a premium.

DHPIM is derived from the PIM where a symbol is represented by a discrete time interval between two successive pulses belonging to two consecutive frames. A pulse represents the dual role of frame initiation and time reference for the proceeding and succeeding frames. This scheme offers shorter frame length and an increase in transmission rate compared to PPM.

In DHPIM, each frame consists of a number of discrete time slots where each header string with duration T_s, also known as one time slot is located at the start of a frame. A symbol is therefore represented by a discrete time interval between two successive headers belonging to two consecutive frames.

For the DHPIM signal with M bit on off keying (OOK) word, the maximum number of time slots in each sampling period is $n = 2^M$. Depending on the most significant bit (MSB) the frame generated will have two different headers namely #0 and #1 and information time slots. For the MSB = 0, each frame consist of a header #0 displaced from the previous header by a number of time slots proportional to the decimal value of the input data. For the MSB = 1, each frame starts with a header #1, followed by a number of time slots corresponding to the decimal value input data after taking its 2's complements, as shown in Figure 2-1.

Figure 2-1 illustrates the comparisons between OOK, PPM, PIM and proposed DHPIM basic waveforms. The first waveform represents two data symbols having 2_{10} and 15_{10} with on off keying data structure. The second waveform is the conventional Pulse Position Modulation signal describing the same two symbols. The pulse interval modulated signal is shown in Figure 2-1 (c). Dual header pulse interval modulated signal has the maximum information rate and is shown in Figure 2-1 (d).

2.1 DHPIM Code Properties

DHPIM is a Pulse Time Modulation technique in which data is encoded as a number of discrete time intervals, or slots, between adjacent pulses. The symbol length is variable and is determined by the information content of the symbol. As shown in Figure 2-1, an additional guard slot is added to each symbol immediately following the header. Guard slot is the zero power time gap which avoids row of pulses in which the time between adjacent pulses is zero. For example, if 0_{10} 0_{10} are transmitted, the transmitter will produce a Header#0 followed by a guard slot and another Header#0 which represents the second symbol. Thus, a symbol which encodes M bits of data is represented by a pulse of constant power in one slot followed by k slots of zero power, where $1 \leq k \leq \frac{L}{2}$ and $L = 2^M$. For comparison, OOK and PPM symbols are also shown in Figure 2-1. The minimum and maximum symbol lengths are 2Ts and $(\frac{L}{2} + 1)$ Ts, respectively, where Ts is the slot duration. For a given value of M, the duty cycle of PPM symbols remains fixed, unlike DHPIM symbols which vary since the symbol length varies. Thus, a

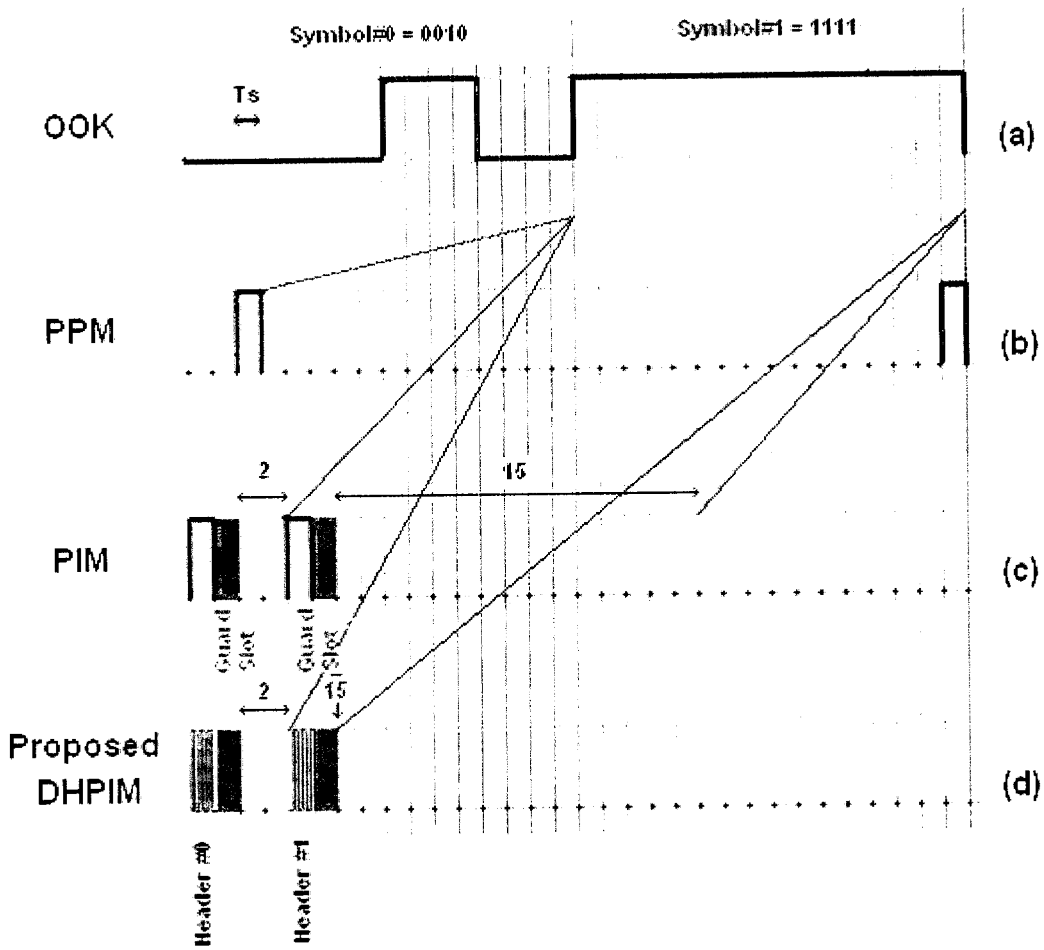


Figure 2-1 Basic 16DHPIM Symbol Structure Versus OOK, PPM, and DHPIM.

DHPIM encoded pulse stream has a higher average transmitted power than a pulse stream which is encoded using PPM since, on average, the symbol length is shorter.

For a DHPIM system encoding M bits of data per symbol, if the slot duration is chosen such that the maximum symbol duration is equal to the time taken to transmit M bits of data using OOK, $T_{M,OOK}$, the slot duration is given as $T_S = T_{M,OOK} / (\frac{L}{2} + 1)$ and the slot frequency is given by $f_S = [(\frac{L}{2} + 1)/M]\,B$, where B is the data bit rate. Note that the data rate of DHPIM is not constant. Assuming that the symbol length is random and uniformly distributed between 2 and $\frac{L}{2} + 1$ slots, the average bit rate, Rb, is given as $Rb = M / \bar{n}Ts$, where $\bar{n} = (\frac{L}{2} + 3) / 2$ is the mean symbol length in slots. The bandwidth required to support communication at a bit rate of Rb based on the average symbol duration, relative to OOK, is given as $W = (\frac{L}{2} + 3)Rb / 2\log_2 L$. DHPIM displays a higher transmission rate than PPM, since conversion is reinitiated immediately after the previous count value has been established; no additional time is wasted waiting for the expiration of a longer predetermined counting period. If the transmission rate for PPM is M b/symbol, the information rate for DHPIM will be;

$$C_{DHPIM} = Modulation\_Level \frac{PPM\_Symbol\_Length}{DHPIM\_Transmission\_BW}$$

$$= Modulation\_Level \frac{PPM\_Symbol\_Length}{DHPIM\_Avg\_Symbol\_Length}$$

$$= M\frac{2^M T_{S\_PPM}}{(2+2^{M-2})T_{S\_PPM}} = \frac{M2^M}{2+2^{M-2}}$$

As M increases, the information rate approaches $4M$ b/s, quadruplet of OOK or PPM, as expected, since on the average a DHPIM symbol with no guard slot will be only one forth the length of an OOK or PPM symbol.

2.2 DHPIM Spectral Properties

Spectral profiles resemble a general sinc envelope shape which contains DC and potential distinct slot components and its harmonics. The amplitude of both components and locations of the slot component largely depend on the bit resolution and the pulse duty cycle (Aldibbiat, Ghassemlooy, and Saatchi, 190).

With the Gaussian doublet signal with bi polar headers, Power Spectral Density (PSD) contains minimal DC component which decreases with M greater than 6 (Aldibbiat, Ghassemlooy, and Saatchi, 189). Since proposed system has M = 8, the unwanted DC terms is greatly minimized theoretically (Nakache and Molisch, 9).

According to the project report of Nakache and Molisch, the random time hoping and polarity flipping of transmitted pulses eliminate the spectral noises which degrade the transmission performance. The proposed system has random time varying headers and antipodal signal structure. This closely agrees to mitigate the spectral noise problem caused by the conventional PPM systems. Moreover, during system simulation, the spectrum of the transmitted data stream indicates that the proposed system has no spectral noise spikes revealing the improved spectral performance.

2.3 Transmission Power

Unlike other communications methods, which transmit continuous signals (100% duty cycle) and the peak power equals the average power, with UWB, the symbol duration Ts is much shorter than the symbol repetition time T_f. This results in a pulse peak power almost hundreds of time larger than the average power as described in Table 2-1. Overall, DHPIM requires lower peak transmission power (Aldibbiat, Ghassemlooy, and Saatchi, 190).

Table 2-1 Transmitted Power.

	PPM	PIM	DHPIM
Average Power Requirement	$\frac{\text{Peak Power}}{2^M}$	$\frac{\text{Peak Power}}{2+2^{M-1}}$	$\frac{\text{Peak Power}}{2+2^{M-2}}$

As an example, UWB system is considered to calculate the output power of the transmitter. Since the upper UWB Power Spectral Density limit is -41.3 dBm/MHz, for the 7500 MHz bandwidth, PSD limit will be 0.56 mW. In other words, if the transmitter is outputting continuous signal, the output power cannot be more than 0.56 mW in order to avoid spectrum violation. However pulse position modulated signals are transmitted once every 256 time slots and the peak power can be 0.56 x 256 = 153 mW. This still offers the average power of -41.3 dBm/MHz. For a DHPIM system, the average rate where each header is transmitted has to be considered. Since the proposed system has M = 8, the average transmission rate is once every 64 time slots. Therefore the peak transmitting power will be 0.56 x 64 = 38 mW. Figure 2-2 (a) represents two symbols in OOK format. Peak power comparison between PPM and DHPIM is shown in Figure 2-2

(b) and (c).

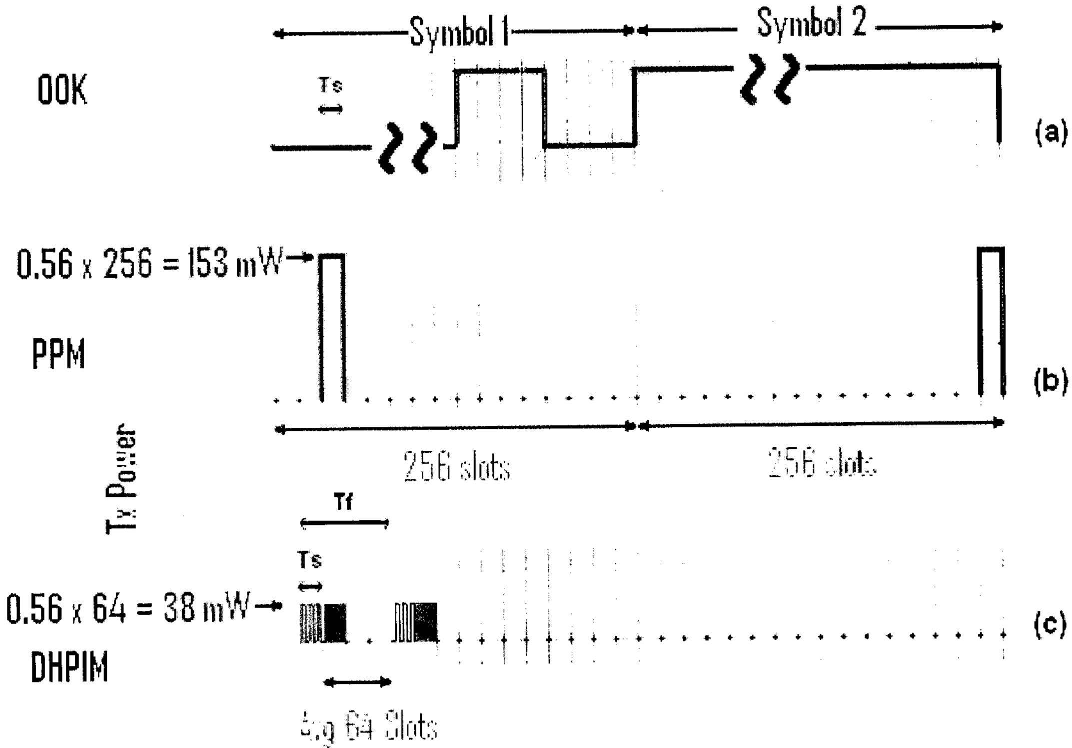


Figure 2-2 Peak Transmitted Power of PPM and 256DHPIM.

3 Wireless Transmission System

Wireless Communication, as the name indicates, is the communication technology without wires, using wireless signals and waves. Among various wireless standards, a modern communications system known as Ultra Wide Band is considered as a transmission scheme to convey the information sent by the transmitter. Data are transmitted as very narrow baseband pulses, typically on the order of nanoseconds, spread energy in Ultra Wide Bandwidth in the order of GHz. Therefore a large transmission rate is achievable. Pulses are sent as bursts and data are encoded in time duration between two headers. The Ultra Wide Band refers to a system or signal with an extremely large bandwidth. UWB signals are defined as signals having a fractional bandwidth of at least 0.2 or occupying at least 0.5GHz spectrum (United States: Federal Communications Commission). The fractional bandwidth η is defined as:

$$\eta = 2\frac{f_{H\_10dB} - f_{L\_10dB}}{f_{H\_10dB} + f_{L\_10dB}}$$

where f_{H_10dB} and f_{L_10dB} represent the highest and lowest -10dB bandwidth frequencies of the signal spectrum, respectively (Randall, 12).

3.1 Features of UWB System

Ultra Wide Band technology can deliver large amounts of data with very low power spectral density. The UWB radio concept is very attractive as it promises to open large amounts of spectrum to a variety of users and at the same time it claims to cause minimal interference between users. Unlike conventional wireless communications systems that are carrier based, UWB based communications is baseband. It uses a series of short pulses that spread the energy of the signal from near DC to a few GHz. One typical technique is to assign a window in time and shift the position of the pulse within that window. This is a classical Pulse Position Modulation (Scholtz).

Since the bandwidth of UWB signals is much wider than that of conventional wireless systems, a higher channel capacity can be achieved even in a low SNR environment. According to Shannon's theorem:

$$C = B\log_2(1+\frac{S}{N})$$

where C is the channel capacity, B is channel bandwidth, and S/N is the signal to noise power ratio at the input to the receiver (Randall, 23). For example, a UWB system that utilizes a 2 GHz spectrum operating in 0dB SNR, its channel capacity can be calculated as $C = 2\log_2(1+1) = 2$Gbps. Based on this result, it can be observed that a UWB system with low signal power may still maintain a high data rate.

Because of the low signal power and the available large bandwidth, the UWB system performance is similar to the spread spectrum system. However compared to the more common forms of spread spectrum such as frequency hopping and direct sequence systems, the UWB system does not rely on a spreading sequence and a hopping sequence to generate the wide bandwidth signals. Instead, it is the extremely short duration of the UWB basic pulse that gives the system its Ultra Wide Bandwidth. Compared to other narrow band communication systems, which operate in the bandwidth limit regime, the UWB system works in the power limit regime as shown in Figure 3-1. Therefore, UWB signal power in any single narrow frequency channel is very small and the interference to any other existing products can be ignored in principle. In case multiple UWB devices are operating within the same small area, the accumulated UWB signal power may have an effect upon other wireless systems. The exact influence level needs to be found out in order to estimate the potential problem.

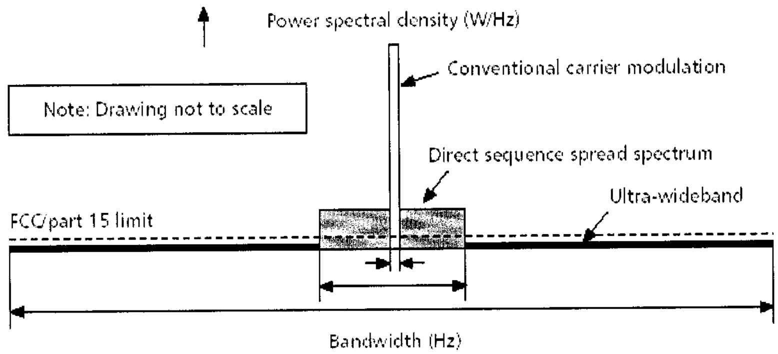


Figure 3-1 Bandwidth-limit Regime vs. Power-limit Regime.

3.2 FCC Regulations on UWB Products

For the legal use of UWB products, the Federal Communications Commission (FCC) released initial rules in February 2002 (CT Federal Communications Commission). The main concern is about interference with existing radio systems. The spectrum that the FCC has proposed for UWB devices now is also being used by 5GHz WLAN, Global Positioning System and Ground Penetrating Radar. Therefore, the allowed transmission power for UWB equipment is restricted to a very low level to avoid interference to those systems, as shown in Figure 3-2. One of the core limitations of UWB devices is that transmission range is limited to around 10 meters due to low transmit power. In addition to this challenge, energy conservation is a high priority in many UWB applications as high transmit power requirements adversely affect battery life.

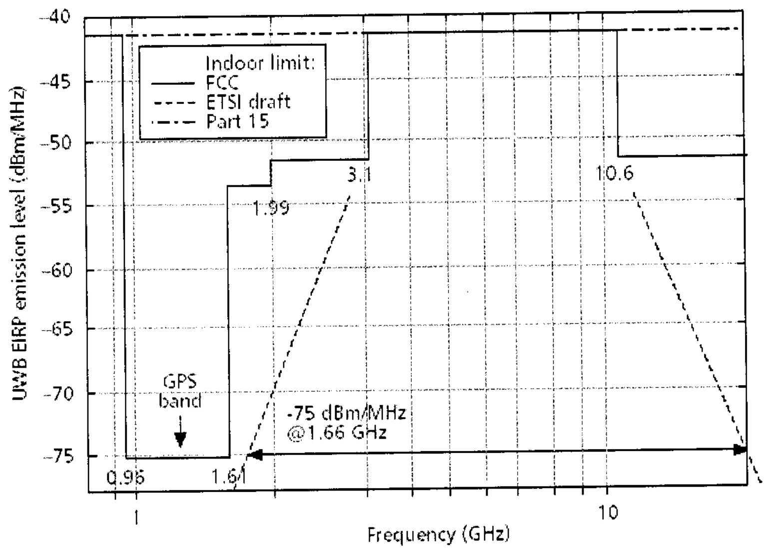


Figure 3-2 UWB Specifications for Indoor Situations.

Source: Porcino, Domenico. "Ultra Wide Band Radio Technology: Potential and Challenges Ahead." Philips Research, IBM Zurich Research Laboratory, Page(s): 69.

3.3 UWB Signal Analysis

Two types of waveforms have been proposed for impulse radio, including the Gaussian monocycle and Raised Cosine pulse. These two pulse shapes are investigated because they comply with the FCC specifications. In general, in choosing a waveform, the goal is to obtain a flat frequency spectrum of the transmitted signal over the bandwidth of the pulse and to avoid a DC component (Porcino, 69).

3.3.1 Single Pulse Representation

The derivation and the comparison of these two pulse shapes are as follow.

Gaussian monocycleA

Gaussian monocycle is a wide bandwidth signal, with its center frequency and its bandwidth related and dependent on the pulse width. In the time domain, the

Gaussian monocycle is mathematically represented as:

$$gm(t) = \frac{t}{\tau} e^{-(\frac{t}{\tau})^2}$$

where τ is a time constant that determines the monocycle duration. In the frequency domain, a Gaussian monocycle's Fourier transformation is:

$$GM(f) = -j.\pi.\sqrt{\pi}.f.\tau^2.e^{-\pi^2 f^2 \tau^2}$$

The center frequency f_c should satisfy:

$$2 f_c^{\,2} \pi^2 \tau^2 = 1$$

It can be seen that f_c is proportional to the inverse of τ and the -3dB bandwidth is about 116% of f_c as explained in the Appendix A. Pulse width is defined as approximately 5τ , which is 0.165ns when t = 0.033ns. Thus, for example for a τ = t 0.033ns monocycle, the center frequency is about 6.85 GHz and its 3dB bandwidth is approximately 7.5 GHz. A pure Gaussian pulse does not fit the FCC rules well. Additional modification is required in the realistic implementation. For example, filtering the Gaussian monocycle before sending it into the air is one of the options which can be implemented.

Raised Cosine Pulse

In the FCC specification, the allowed PSD mask for UWB signal is a rectangular shape. It is obvious that the Gaussian shape pulses do not match with this rule perfectly.

Therefore, the Raised Cosine pulse is introduced to provide a better matching with the FCC mask, which is shown in Figure 3-2. The Raised Cosine pulse can be described in the frequency domain as:

$$H(f)=\begin{cases} 1, & |f|<f_s \\ \frac{1}{2}\left\{1+\cos\left[\frac{\pi(|f|-f_1)}{2f_\Delta}\right]\right\}, & f<|f|_s<B \\ 0, & |f|>B \end{cases}$$

where B is the absolute bandwidth. f_1 and f_Δ are given as:

$$f_\Delta = B - f_{6dB} \text{ and } f_1 = f_{6dB} - f_\Delta$$

where f_{6dB} is the -6dB frequency of the raised cosine pulse. For the aim of utilizing the whole 7.5 GHz FCC approved bandwidth, the value of f_{6dB} is set to 3.75 GHz.

Its corresponding time domain waveform is calculated as:

$$h(t)=F^{-1}[H(f)]=2f_{6dB}\left(\frac{\sin 2\pi f_{6dB}t}{2\pi f_{6dB}t}\right)\left[\frac{\cos 2\pi f_\Delta t}{1-(4f_{\Delta t})^2}\right]$$

Since $h(t)$ is the low frequency band signal ($-f_{6dB}+f_{6dB}$) it needs to be shifted to the desired frequency band. For example, if the Raised Cosine pulse spectrum utilizes the frequency spectrum of FCC approved band, the baseband pulse should be up converted to the central frequency f_c (6.85GHz). Therefore, the transmitted pulse will be

$$rc(t) = h(t).\cos(2\pi f_c t)$$

3.3.2 Pulse Shape Selection

By comparing two proposed pulse shapes, it was determined that the Raised Cosine pulse might have suitable spectral properties which fits FCC approved rectangular mask very well. However it is hard to generate by a simple circuit, mainly because Raised Cosine pulses have a non-realistic side lobe in the time domain and generating such a pulse is too difficult for the circuits.

On the other hand, the Gaussian monocycle is relatively simpler to generate, and therefore it is chosen as the pulse shape to be utilized in this project. In the real system, antenna has the derivation effect which transforms the shape of the transmitted pulse significantly. For this reason, system simulation was carried out using Gaussian doublets as the transmitted pulses.

4 Direct Sequence Spread Spectrum

To improve the capabilities of UWB technology, traditional spread spectrum techniques are incorporated in the system. In this chapter, the attractive features of direct sequence spread spectrum (DSSS) with orthogonal signaling are described. Performance of DSSS UWB communication systems, in terms of processing gain and data rate bounds are evaluated.

4.1 Pulse Train and Pseudo Random Pulse Location

The stream of headers to be transmitted is represented by two Pseudo Random (PN) headers, namely Header#0 and Header#1. The signal sequences of Header#0 and Header#1 are 0011 0001 1000 and 1100 1110 0111, respectively. Zero (0) is represented with negative polarity Gaussian doublet and one (1) is represented with positive Gaussian doublet. Each bi polar header is allocated across to a frequency channel across the UWB spectrum. A data symbol at the point of transmission is combined with a higher data rate bit sequence.

In the frequency domain, the highly regular pulse train produces power spikes at regular intervals of $1/T_f$; where T_f is the frame period (Nakache and Molisch, 56). Thus, the already limited low UWB signal power spreads among the spectral lines. This periodic pulse train does not utilize the spectrum resource efficiently and needs to be improved. Therefore, it is important to achieve the flat PSD, so that the transmission power can be maximized under the FCC specifications. The key to optimize the spectrum usage is to smooth out the spectral lines. DHPIM removes the obvious correlation of the periodic pulse trains in the time domain. This is because DHPIM pulses appear purely random. Consequently, unwanted spectral lines are suppressed because there is no correlation information in the pulse position.

4.2 Processing Gain

UWB systems occupy a bandwidth approximately 700 MHz; due to the large bandwidth factors and low power spectral densities, the spreading code was proposed. Moreover, many transceivers can coexist in the same bandwidth using different spreading codes.

In the proposed system, a train of pulses is sent and information is conveyed by the position and the polarity of the pulses, which correspond to DHPIM. Each information symbol is represented not by one pulse but by a sequence of pulses, and the location of the pulses within the sequence is determined by a pseudo random sequence. Therefore, if the project is further upgraded to work as a multi-user system, pseudo random header pulses will prevent catastrophic collisions among different users and thus provide robustness against multiple access interference.

Spreading codes improves interference rejection factor in the proposed system structure. The Processing Gain (PG) of 12 chips for each Header can be obtained as:

$$PG \doteq 10 \log 12 \doteq 10.8 \text{ dB}$$

It is obvious that this processing gain will be 0 dB if only a single pulse is used to represent the Header#0 and the Header#1.

4.3 Transmitter Power

In this paper, the transmitter radiates sequences of Gaussian monocycles. The analyses discussed by Porcino showed that the transmit antenna acts as an ideal derivator.

Also, 83% of the overall energy is contained in the spectral range between 3.1 and 10.6 GHz. The available bandwidth is 10.6 – 3.1 = 7.5 GHz. Since the upper PSD limit is -41.3 dBm/MHz, for the 7500 MHz bandwidth, the PSD limit will be

$$= -41.3 \text{ dBm} + 10 \log 7500$$

$$= -41.3 + 38.75$$

$$= -2.55 \text{ dBm/7500MHz.}$$

In other words, transmit power of P_{Tx} = -2.55 dBm $\equiv$ 0.55 mW can be used to have perfect utilization of the provided UWB spectral range. From section 2.3, Peak Power of either Header #0 or Header #1 is

$$\text{Peak Power} \quad = P_{Average}\,(2+2^{M-2})$$

$$= P_{Average} \text{ x } 66 = 36.7 \text{ mW.}$$

The above peak power will be shared by 12 PN chips. Therefore each chip has 36.7 / 12 = 3.06 mW peak power. For the transmit antenna with 50 Ohms characteristics impedance, each chip can have a 0.390 peak voltage driven to the antenna.

5 System Simulation Model

Simulations were performed using Simulink, MATLAB (R14). The goal of the system simulation is to derive specifications for the receiver and the transmitter building blocks and to study the system performance. Existing knowledge of the UWB system, DHPIM technology, transmission power spectrum, and wireless channel noise were carefully implied to adapt with current standard technology.

5.1 Transmitter and Receiver

The data rate varies from 7.8 Mbps to 500 Mbps. If the transmit integer data is linearly distributed from 1 – 256, the average data rate is $\frac{7.8M + 500M}{2} \approx 250\,\text{Mbps}$. Because DHPIM data rate is variable, the data is generated from the MATLAB input data file. The channel is distortion free (Multi-path dispersion is ignored). The receiver noise (shot noise and thermal noise) is assumed to be negligible. The variation in received signal strength resulting from various path losses is ignored. An error in any slot of the packet will invalidate the entire packet.

The block diagram for a typical DHPIM transmitter is shown in Figure 5-1. Initially, 8 bits of data are loaded into the latch and the counters are reset. The UP and DOWN counters are incremented by the slot frequency clock. The magnitude comparators compare the data held in the 8 bit latch with the output from the counters, and go high when the two become equal. Header #1 / Header #0 is generated if the data is >128 / <129. Generated header indicates the start of the next symbol. The positive edge of this pulse is used to load the next 8 bits into the latch and reset the counters. The outputs of the comparators are connected to a PN generator which transmits either one of two different PN sequences at a time.

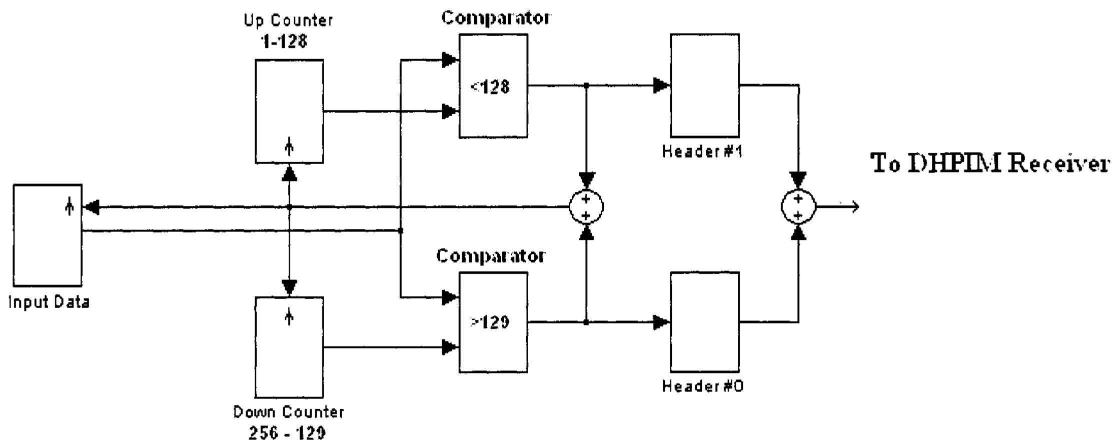


Figure 5-1 DHPIM Transmitter.

The block diagram for a DHPIM receiver is shown in Figure 5-2. Decoding the DHPIM signal is a relatively simple process compared to PPM and is performed by counting the number of discrete time slots between two successive headers. The correlation receiver improves the receiver sensitivity by approximately 10.8 dB. The receiver front end block matches the incoming pulses at signaling rate of 0.6 n seconds. Two sequence correlators are used to correlate the incoming headers. A threshold detector is then used, with the threshold level set to the peak amplitude of the received pulses at the sampling instant which is the 12th sampling point of the header string. The output from the threshold detector represents an estimate of the transmitted DHPIM pulse stream. The recovered slot clock is used to generate the sampling points and count the number of slots between adjacent headers. The positive edge of the incoming DHPIM pulse is used to load the value of the counter into the data latch, and the negative edge then resets the counter.

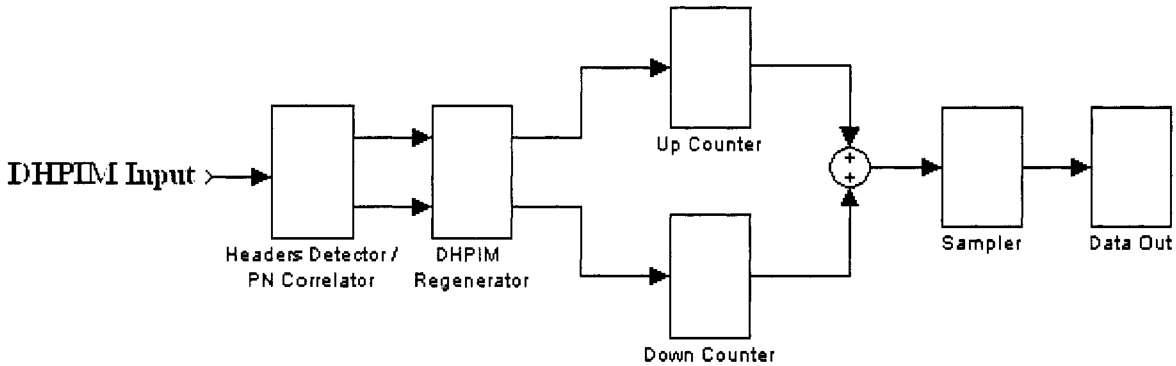


Figure 5-2 DHPIM Receiver.

5.2 Detection by Correlation

As explained in the previous section, each header is coded into a sequence of 12 chips of duration 7.2 nsec. Figure 5-3 (a) is the received signal represented by the sequence of 12 bits, Header#1. A correlation receiver is used to determine whether the Header#1 or Header#0 was transmitted. The correlation receiver produces the decision variable at the 12th sampling time.

Figure 5-3 (c) illustrates the recovery of the Header#1 signal at the receiver. The receiver's own copy of the spreading sequence is synchronized with the received version. If the receiver correlates with the incorrect Header sequence, the amplitude at the 12th time slot will be zero as shown in Figure 5-4 (c). This proved that the cross correlation property of two headers sequences allowed receiver to successfully detect headers.

5.3 Data Rate Bounds

According to the current FCC regulation, maximum permitted transmit power (P_{Tx}) is -2.55 dBm in average. The usable frequency ranges for UWB data transmission

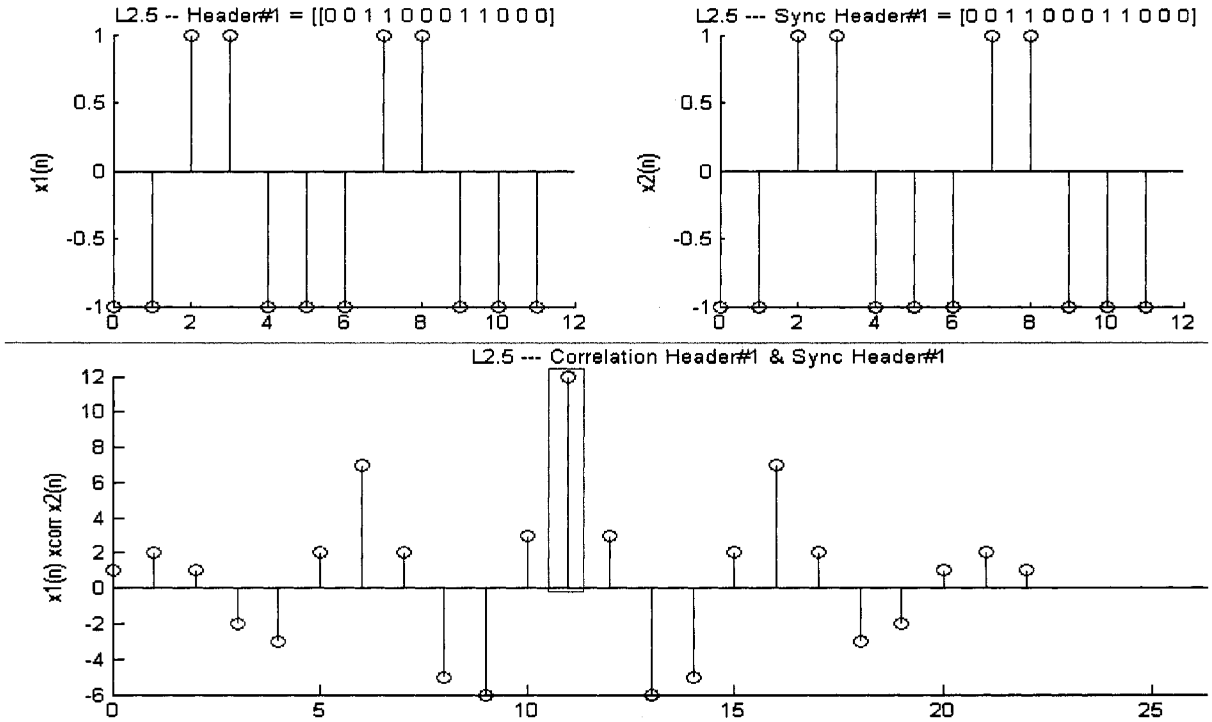


Figure 5-3 (a) Received Header#1 (b) Generated Header#1 (c) Header#1⊕ Header#1.

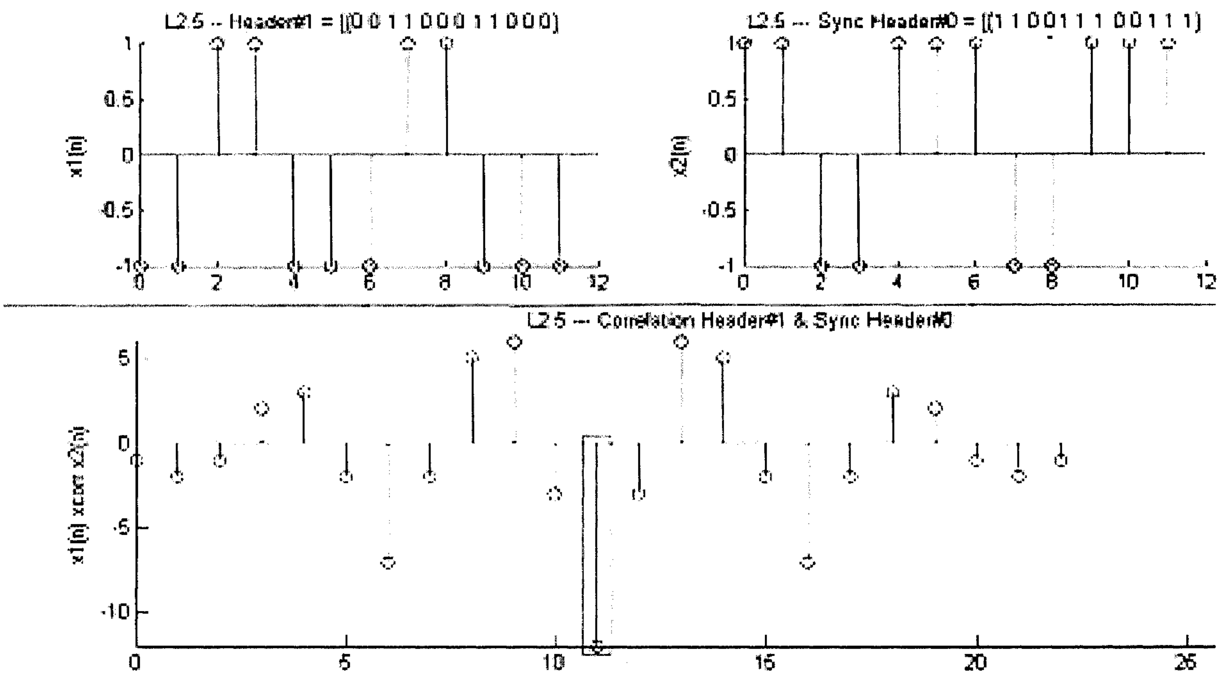


Figure 5-4 (a) Received Header#1 (b) Generated Header#0 (c) Header#1 ⊕ Header#0.

are between 0 and 0.96 GHz and between 3.1 GHz and 10.6 GHz.

To gain an overview on the potentials of the UWB, it is very useful to look at the bound corresponding to the minimum and maximum data rates. Average data transfer rate is calculated as a mean number with the assumption that transmitted 8 bit data is linearly distributed from 00 $_{\text{Hex}}$ to FF $_{\text{Hex}}$.

The modulation order of 8 provides 256 time slots. The proposed DHPIM has longest time slot of 128 + Guard Band because the system decodes lower and upper 128 slots with Header#0 and Header#1, respectively. The bit stream of 1111 1101 is sent using DHPIM as shown in Figure 5-5. The header is represented by the Header#1, a 12 PN sequence.

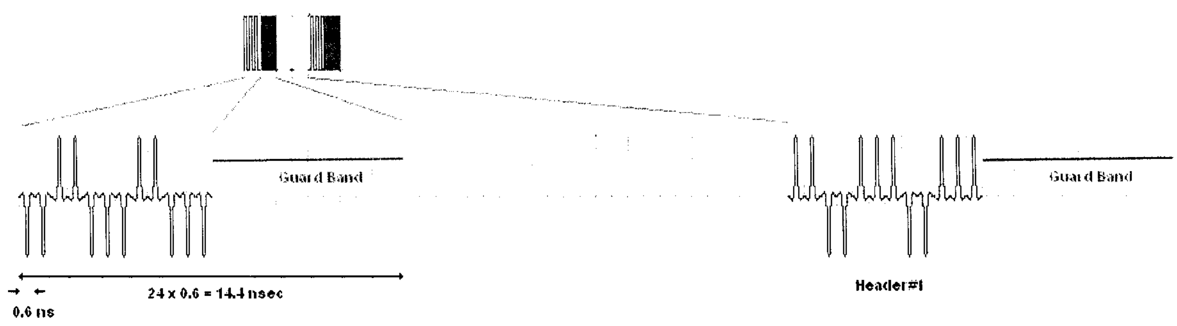


Figure 5-5 Modulation Order, M = 8. Sample Bit Stream 11111101.

Chip Rate is $\frac{1}{0.6n}$ chips/seconds as shown in Figure 5-3. Maximum data transfer rate is achieved when 12 chips and guard band are transmitted; that is, to transmit a bit stream of either 0000 0000 or 1111 1111. Each time slot contains 12 chips and is 8 nsec long. Therefore total time taken to transmit 12 chips and the quiet guard time slot will be 2 x 8n = 16 nsec. This provides a maximum bit rate of ($\frac{1}{16n}$ symbols/seconds) x (8 bits/symbol) = 500 Mbps. Minimum bit rate occurred when the bit stream becomes 1000 0000 or 0111 111. This bit pattern will result minimum bit rate of

$(\frac{1}{3\text{n}\,(128+1)}$ symbols/seconds) x (8 bits/symbol) = 7.8 Mbps. If the bit stream

distribution is linearly distributed, the average bit rate of proposed DHPIM system

is $\frac{500M + 7.8M}{2} \approx 250\,\text{Mbps}$.

5.4 Summary on OOK, PPM, and DHPIM Time Durations

Equations below briefly describe the main points for a DHPIM system with levels of modulation, M = 8, slot duration = T_S, OOK bit duration = Tb, and OOK bit rate = R_b.

DHPIM Frame lengths: $\quad$ L min $= 2T_S$

$$\text{L max} = (2 + 2^{M-1})T_S = 130\,T_S$$

$$\text{L avg} = (2 + 2^{M-2})T_S = 66\,T_S$$

OOK frame duration: $\quad T_f = \text{M}\,Tb = \frac{\text{M}}{R_b}$

DHPIM average slot duration: $\quad Ts(avg) = \frac{T_f}{L_{avg}} = \frac{\text{M}}{R_b} \div L_{avg} = \frac{\text{M}}{R_b 66}$

DHPIM transmission bandwidth: $\text{BW}(avg) = 1/Ts(avg) = \frac{R_b 66}{M}$

5.4.1 Simulated Data

Figure 5-6 represents the example of simulated data using the DHPIM technique. The first waveform represents the 8bit/symbol data in the integer format. The bit rate corresponds to a conventional PPM which transmits 8bits every 2048 n seconds. DHPIM has variable bit rate of minimum 16 n seconds to maximum 1032 n seconds. The second waveform is simply the integer representation of the transmitted DHPIM data. The third waveform bursts are the transmitted DHPIM data. Simulated results revealed that the DHPIM scheme has approximately 4 times faster bit rate than the conventional 8bit/symbol transmission.

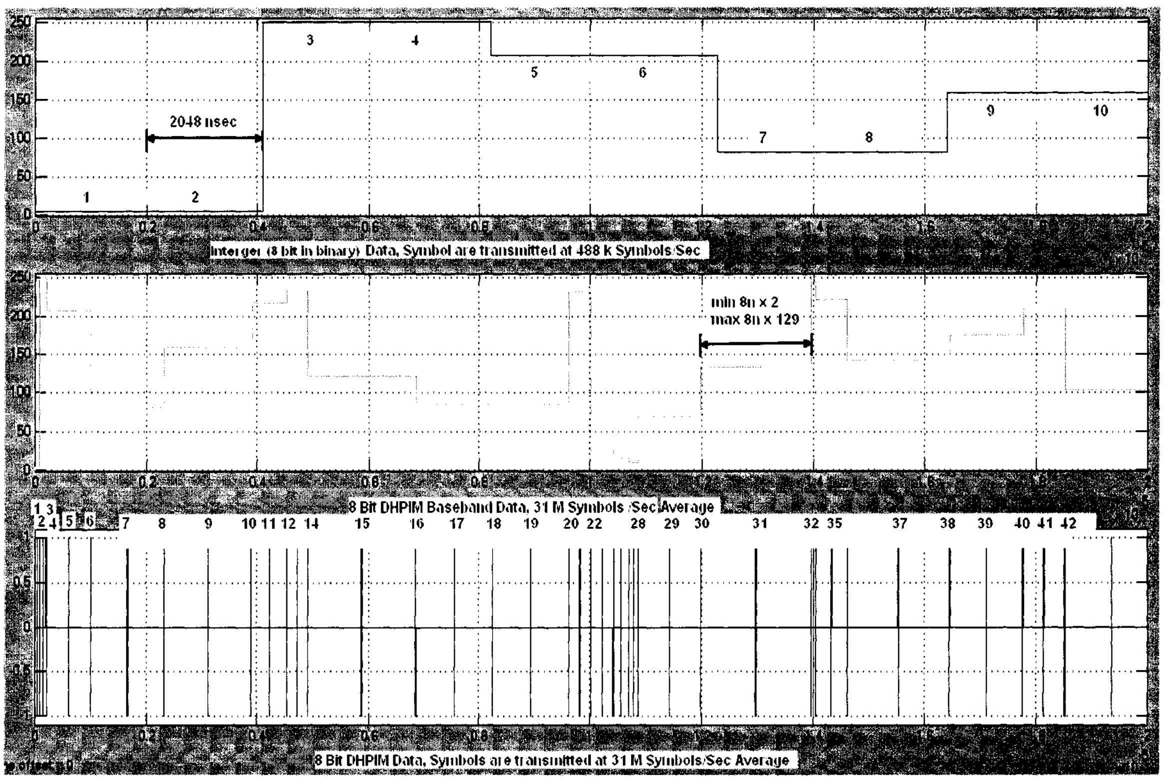


Figure 5-6 DHPIM Average Data Rate is Approximately 4 times Higher than PPM.

5.5 Pulse Detection by Simulation

Several pulse detection simulations are explained within this section based on the proposed transmit signal referenced pulse detection method. The results are shown by a number of captured outputs from the simulation. The received UWB signal with noise, together with filtered result is shown in Figure 5-7 to elaborate the detection performance. Header correlator block in Figure 5-2 produces the highest peak when the received header matches with the regenerated header string. The above result was captured when Header#0 and Header#1 were sent in the minimum frame period, that is 16 nsec. The receiver sampled at the peak of the correlated data. Figure 5-7 and 5-8 illustrate the system robustness at Es/No = 1 dB.

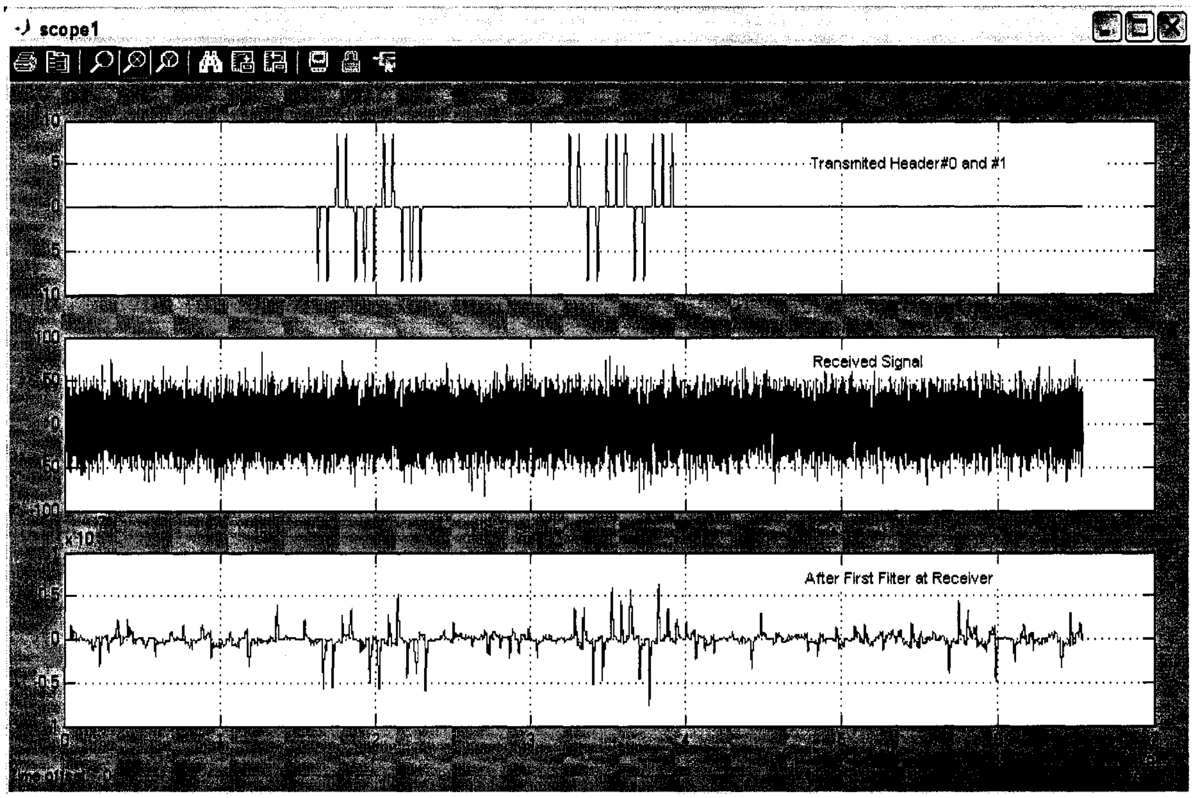


Figure 5-7 Two Received Headers, Es/No = 1dB.

5.6 Frequency Spectrum Analysis

In the transmitted spectrum, slot component and its harmonics are present and nulls at even multiple of slot frequency (Porcino, 70). Therefore, the Phase Locked Loop (PLL) cannot be used to extract the slot frequency component. However the slot

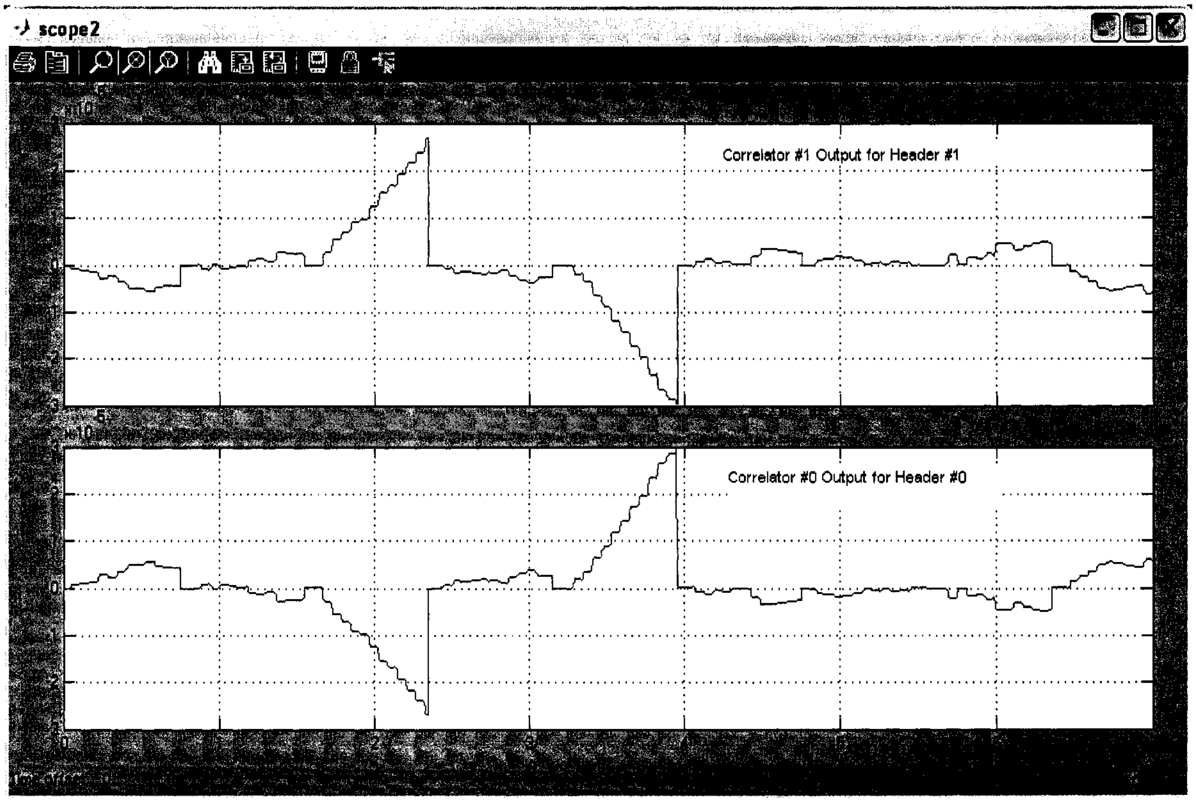
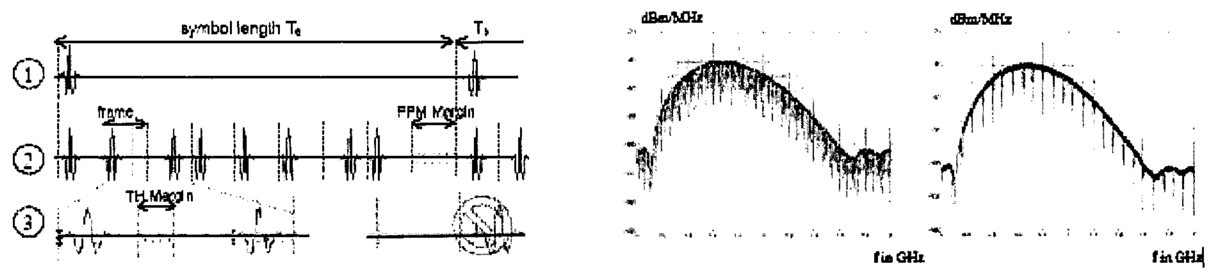


Figure 5-8 Received Header Correlation, Es/No = 1dB.

frequency can be extracted by employing a non linear device followed by a PLL circuit. Unlike PPM, the DHPIM has variable symbol duration; that is, symbol boundaries are not known prior to detection. Thus practical implementation of maximum likely sequence detection is not feasible, even in the absence of Inter Symbol Interference (ISI). Therefore, the most practical implementation of DHPIM detection would be hard decision.

In the frequency domain, the highly regular monocycle pulse train using the PPM produces power spikes at regular intervals as shown in Figure 5-9 (Nakache and Molisch, 32). Thus, the low UWB signal power spreads among the spectral lines. But if the PSD is flat, then the transmission power can be maximized under the FCC specification. It is clear that this periodic pulse train does not utilize the spectrum resource efficiently and needs to be improved.

For smoothing the spectral lines, which is the key to optimize the spectrum usage, DHPIM automatically removes the obvious correlation of the periodic pulse train in the time domain. This is an admirable method for making the pulses to appear random in time. Thus excessive correlation is avoided in the pulse train and the spectral lines are suppressed. Figure 5-10 describes the pulse train with randomly located Gaussian doublets.



(a) (b)

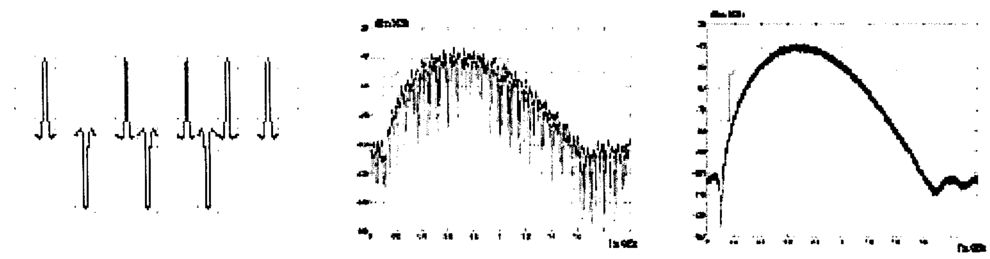
Figure 5-9 (a) Symbol Structure (1) One pulse/symbol (2) DSSS Sequence (3) Frame.

(b) Spectrum of M-ary PPM with M=2 (Left) and M=8 (Right).

5.7 Power Analysis

In the FCC specification, the power limit for the frequencies from 3.1 GHz to 10.6 GHz is -41.25 dBm/MHz. Since the working frequency band is 7.5GHz bandwidth in total, the upper limit of the transmission power (P_{Tx}) of the UWB system can be calculated as: P_{Tx} = -41.25 dBm/MHz . 7.5GHz = -2.5 dBm = 0.55 mW.

Based on the value of transmitted power, the received power (P_{Rx}) of the UWB receiver can be calculated by using the UWB channel model. A practical UWB channel model was proposed by the IEEE based on channel measurements (Becker).



(a) (b) (c)

Figure 5-10 (a) Pulse Based Polarity Flipping Sequence.

(b) Spectrum of PPM Signal with Random Sequence.

(c) PPM Signal Spectrum with Random Sequence and Pulse Based Polarity Flipping Sequence.

5.8 Observations

Mitigating Multi-path can be achieved by placing the channel equalizer before the header correlator at the receiver. In order to prevent error propagation, one effective way is by repeating the last integer digit in the transmit data stream with the cost of lowering the overall data transmission rate. For example, if three consecutive integers to be transmitted are 156, 15, and 37, the actual integer transmitted will be 156, 6, 15, 5, 37, and 7 (Hoctor and Tomlinson, 268). This technique will allow the receiver to have error checking capability and to insert a dummy header to avoid error propagation. A conventional hard decision detection scheme is utilized in the simulation model. In other words, the received analog signal is first sampled to form a discrete time signal which is then passed on to the detector. If soft decision is incorporated, the advent of Error

Correction Codes and Parity Check Codes will provides substantial power gains over hard decision detectors. The current simulation model could also be upgraded with the channel equalization to gain the robustness against Multi-path effects.

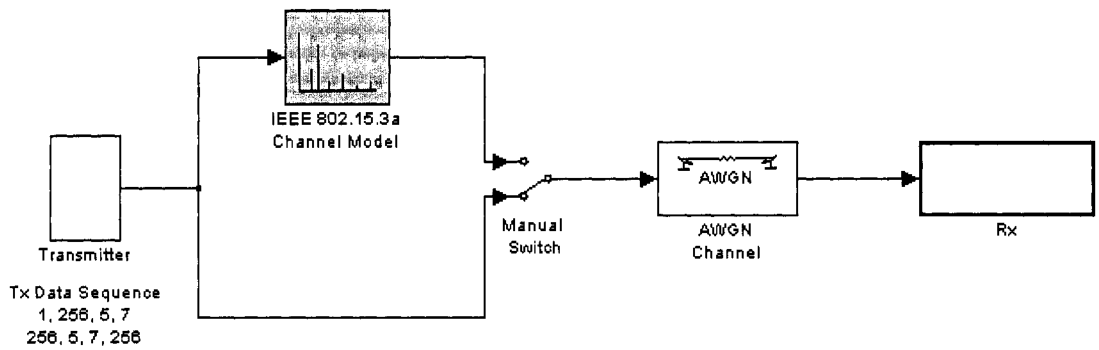


Figure 5-11 System Model with Multi-path Channel and AWGN Noise.

6 Conclusions

DHPIM system for digital communications, as it currently exists, will meet the requirements described in Chapter 1. It was shown that DHPIM, compared with other systems, offers a higher bit rate and simplified receiver structure. The DHPIM transceiver offers many advantages such as a high data rate, transmission security with defined Pseudo Noise, and the ability to reuse the same bandwidth with different PN sequence headers. This would support multiple user systems. The DHPIM system not only solves the problem of frame synchronization associated with the PPM, by using a PN sequence in each frame, but it also improves the transmission capacity and data rate compared to the PPM. In this thesis, the properties of DHPIM for a wireless channel were analyzed by presenting expressions for the pulse train, and power spectral density. Also, the transmit power requirements were presented and compared with those of other modulation schemes. For the DHPIM and the PPM, it was shown that the power requirement depends largely on the value of frame length, L. As explained in chapter 4, for the chosen modulation order, M = 8, the average power to meet the FCC requirement is -2.55 dBm if the UWB is considered as one of the applications.

Unlike other communications methods, which transmit continuous signals and the peak power equals the average power, with DHPIM, the pulse duration (T_s) is much shorter than the pulse repetition time (T_f). The spreading ratio (P) which is defined as the ratio T_f / T_s, is equal to 64 on the average, resulting in a pulse peak power approximately 64 times larger than the average power as mentioned in the section 4.3.

Communication systems utilizing DHPIM scheme work without fixed frame durations. This significantly increases the transmission capacity as much as 4 times that of a regular PPM based systems. The proposed model uses a pulse based polar sequence. This provides a smooth and efficient power spectrum. This allows the receiver to achieve relatively high signal to noise ratio. Moreover, a processing gain is obtained as a result of the PN property and the narrow chip duration of the headers. This processing gain is achieved at the receiver by time gating technique where the sampling instant is matched to the symbol duration.

The research is focused on exploiting DHPIM applications in indoor wireless communications. The modulation order of the transmitted symbols, data rates, header sequences, and transmitted power were carefully chosen to achieve not only a faster bit rate but also a better overall performance.

REFERENCES

Aldibbiat, N., Ghassemlooy, Z., and Saatchi, R. "Dual header pulse interval modulation for dispersive indoor optical wireless communication systems." IEE Proceedings, June 2002. Volume 149, Issue 3, Page(s):187-192.

Becker, Tim. Implementation of the IEEE 802.15.3a UWB Channel Model Project Report, San Jose State University, November 2004.

Hoctor, R., and Tomlinson, H. "Delay-hopped transmitted-reference RF communications." IEEE Conf. UWB System: 265-270, 2002.

Nakache, N., and Molisch, Andreas. Influence of Modulation Format, Multiple Access Scheme and Pulse Shape Project Report, Mitsubishi Electric Information Technology Center America, May 2003.

Porcino, Domenico. "Ultra Wide Band Radio Technology: Potential and Challenges Ahead." Philips Research, IBM Zurich Research Laboratory, Page(s): 66-74.

Randall, Paul. "Telecommunication Systems." EE4 Lecture Series. University of Hertfordshire, United Kingdom. 12 Dec. 1997.

United States, Revision of Part 15 of the Commission's Rules regarding Ultra Wide Band Transmission systems. Federal Communications Commission. Online. Compuserve. February 14, 2002.

APPENDIX: Gaussian Monocycle Bandwidth

The bandwidth of a Gaussian monocycle can be derived as follow.

$$GM(f) = -j\pi\sqrt{\pi}f\tau^2 e^{-\pi^e f^e \tau^3}$$

The energy spectrum of this single Gaussian monocycle:

$$|GM(f)|^2 = \pi^3 f^2 \tau^4 e^{-2\pi^e f^e \tau^3}$$

$$d(|GM(f_c)|^2)/df = 2\pi^3 f_c \tau^4 e^{-2\pi^e f^e \tau^3} - 4\pi^5 f_c^3 \tau^6 e^{-2\pi^e f^e \tau^3}$$

$$2f_c\tau^4 = 4f_c^3\tau^6\pi^2$$

$$2f_c^2\tau^2\pi^2 = 1$$

Therefore, f_c is the reciprocal of τ.

$$|GM(f_{3dB})|^2 = \frac{1}{2}|GM(f_c)|^2$$

$$\pi^3 {f_{3dB}}^2 \tau^4 e^{-2\pi^e {f_{3dB}}^e \tau^3} = \frac{1}{2}\pi^3 {f_c}^2 \tau^4 e^{-2\pi^e {f_c}^e \tau^3}$$

$$\ln 2f_{3dB}^2 - 2\pi^2 f_{3dB}^2\tau^2 = \ln f_c^2 - 2\pi^2 f_c^2\tau^2$$

Let $f_{3dB} = mf_c$, then: $\ln 2 + 2\ln m = (2m^2 - 2)\pi^2 f_c^2 \tau^2$

Substitute $2f_c^2\tau^2\pi^2 = 1$, $\ln 2 + 2\ln m = m^2 - 1$

The value of m is 0.48 or 1.64, thus 3dB bandwidth can be calculated as:

$$BW_{3dB} = (1.64 - 0.48)f_c = 1.16f_c$$